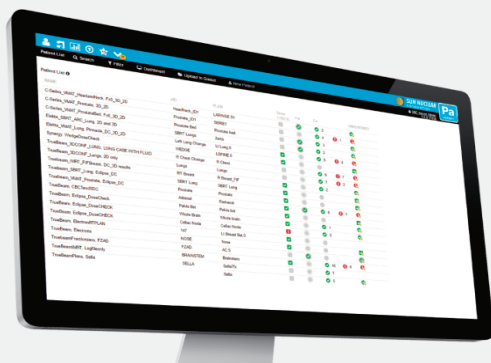


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# Practical Implementation of Patient-Specific Quality Assurance for Small and Multiple Brain Tumors in CyberKnife with Fixed Collimators

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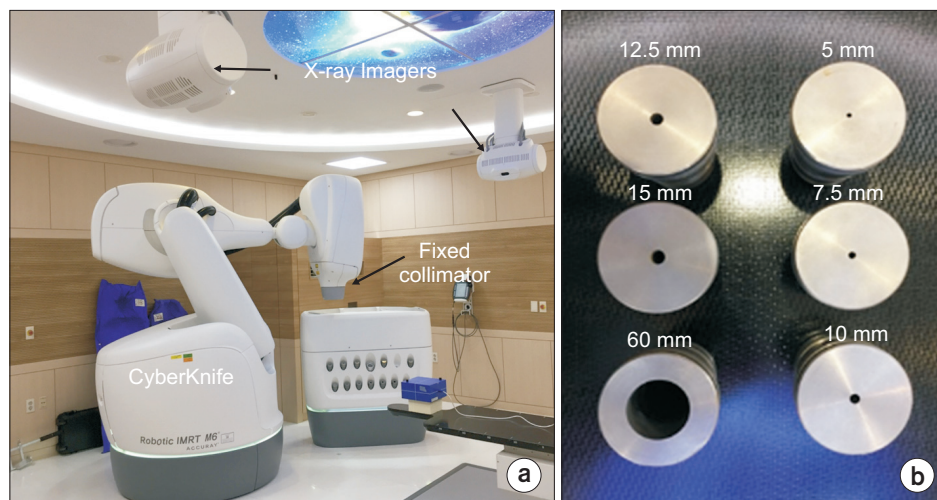
This paper evaluates patient-specific quality assurance (PSQA) in the treatment of small and multiple tumors by the CyberKnife system with fixed collimators, using an ion chamber and EBT3 films. We selected 49 patients with single or multiple brain tumors, and the treatment plans include one to four targets with total volumes ranging from 0.12 cc to 3.74 cc. All PSQA deliveries were performed with a stereotactic dose verification phantom. The A16 microchamber (Standard Imaging, WI, USA) and Gafchromic EBT3 film (Ashland ISP Advanced Materials, NJ, USA) were inserted into the phantom to measure the point dose of the target and the dose distribution, respectively. The film was scanned 1 hr after irradiation by a film digitizer scanner and analyzed using RIT software (Radiological Imaging Technology, CO, USA). The acceptance criteria was <5% for the point dose measurement and >90% gamma passing rate using 3%/3 mm and relative dose difference, respectively. The point dose errors between the calculated and measured dose by the ion chamber were in the range of -17.5% to 8.03%. The mean point dose differences for 5 mm, 7.5 mm, and 10 mm fixed cone size was -11.1%, -4.1%, and -1.5%, respectively. The mean gamma passing rates for all cases was 96.1%. Although the maximum dose distribution of multiple targets was not shown in the film, gamma distribution showed that dose verification for multiple tumors can be performed. The use of the microchamber and EBT3 film made it possible to verify the dosimetric and mechanical accuracy of small and multiple targets. In particular, the correction factors should be applied to small fixed collimators less than 10 mm.

**Keywords:** CyberKnife, Microchamber, EBT3, Patient-specific quality assurance, Brain tumor

## Introduction

CyberKnife M6 (Accuray Inc, Sunnyvale, CA) is frameless and Image-guided robotic radiosurgery system (Fig. 1). It has almost 1000 monitor unit (MU)/min high dose-rate and 6 MV flattening filter free treatment beam with non-coplanar beam geometry. It is suitable to treat for stereotactic radiosurgery (SRS) or stereotactic radiotherapy (SRT) for small and multiple brain tumors. It provides three types

of collimator: fixed collimator, IRIS<sup>TM</sup> variable aperture collimator, and InCise<sup>TM</sup>2 multileaf collimator (MLC).<sup>1)</sup> The IRIS<sup>TM</sup> collimator that allows the field size to be varied during treatment is applicable to a target that may not be spherical in shape requiring multiple collimator sizes. MLC can be considered for multiple brain tumors because fields are shaped to match the tumor closely and the delivery time is reduced. However, due to a limit of leaf width (3.85 mm), it is hard to cover the small size tumor and small



**Fig. 1.** Overview of CyberKnife M6 system: (a) Schematics of CyberKnife mounted with the fixed collimator and x-ray live imagers installed on the ceiling and (b) fixed collimators: 5.0, 7.5, 10.0, 12.5 and 15.0 mm for brain tumors. 60 mm for dosimetric quality assurance.

changes in small field size can significantly affect the dose delivered.<sup>2,3)</sup> For target coverage, the fixed collimator can be a useful modality but it is challenging when patient-specific quality assurance (PSQA) is performed because of lateral electronic disequilibrium, steep dose gradients, and complex dose distribution generated by multi-directional beams.<sup>4,5)</sup> To overcome these issues, we focus on PSQA for multiple brain tumors with small circular photon beams of diameter 5 to 25 mm in CyberKnife with a fixed collimator. In this study, PSQAs were performed with the stereotactic dose verification phantom (SDVP; Standard Imaging, WI, USA), which includes the Exradin A16 microchamber<sup>6)</sup> (Standard Imaging, WI, USA) and Gafchromic EBT3 film (Ashland ISP Advanced Materials, NJ, USA).

## Materials and Methods

### 1. Patient selection and delivery for the small field

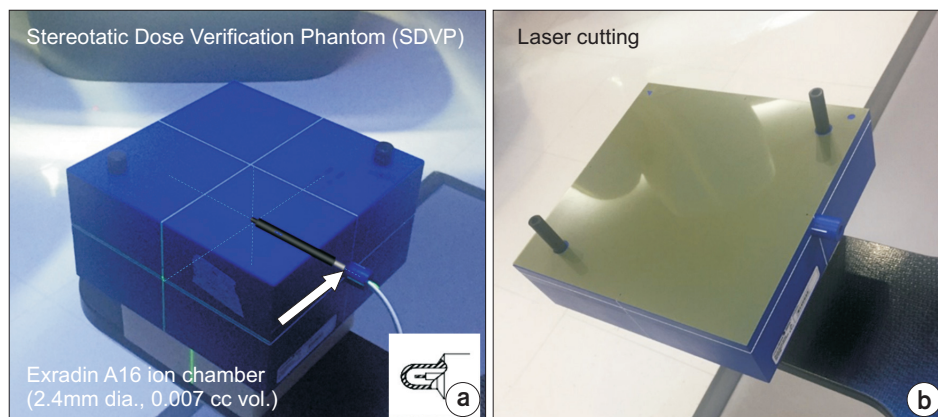
49 patient plans with single or multiple brain tumors were selected for this study. The plans had 1 to maximum 4 targets with total volumes ranging from 0.12 cc to 3.74 cc (diameter 6.1 mm–19.3 mm), approximately. Table 1 shows the characteristics of patient plans. Each CyberKnife plan was created by using a single fixed collimator only.

The accuracy of planning and delivery was evaluated by delivering treatment plans to the SDVP. As Fig. 2, the A16 microchamber (0.007 cm<sup>3</sup>)<sup>6)</sup> and Gafchromic EBT3 film were inserted into the phantom to measure the central

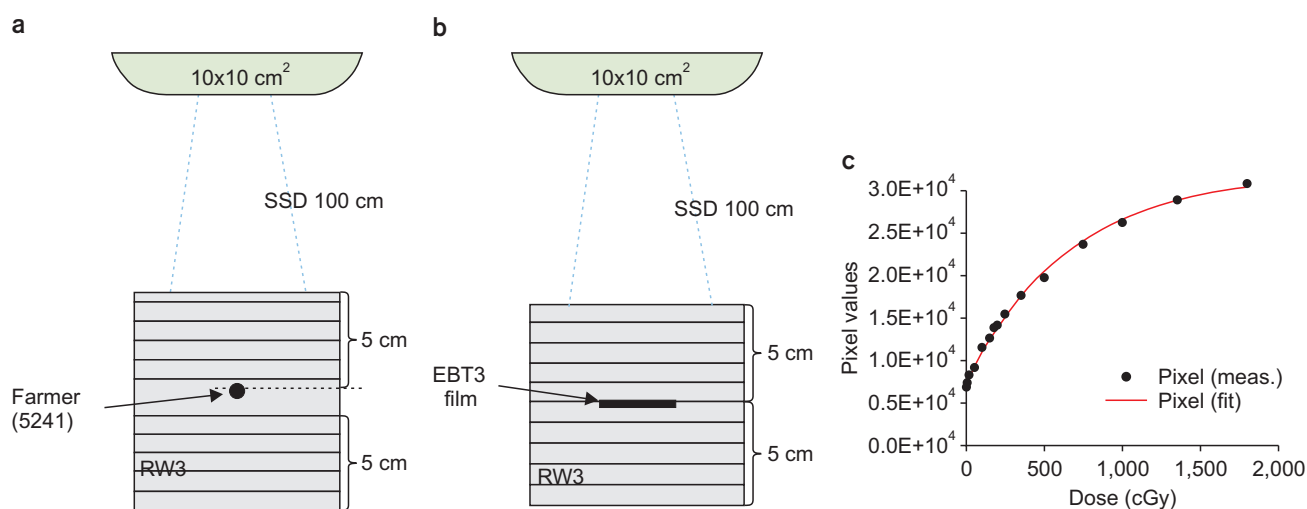
**Table 1.** The properties of CyberKnife<sup>®</sup> plans for brain tumors.

CyberKnife <sup>®</sup> Plans	Number of patients
Fixed cone size	
5.0 mm	9
7.5 mm	12
10.0 mm	15
12.5 mm	9
20.0 mm	3
25.0 mm	1
Total	49
Number of tumors	
1	34
2	9
3	5
4	1
Total	49
Tumor size	
diameter ≤ 7.5 mm	7
7.5 mm < diameter ≤ 10.0 mm	17
10.0 mm < diameter ≤ 12.5 mm	7
12.5 mm < diameter ≤ 15.0 mm	2
15.0 mm < diameter ≤ 17.5 mm	5
17.5 mm < diameter ≤ 20.0 mm	5
20.0 mm < diameter	7
Total	49

dose of the target and relative dose distribution, respectively. EBT3 film was cut by using Laser cutting system.<sup>7)</sup> The 4 gold fiducial markers within the SDVP phantom were used for matching between live digitally reconstructed radio-graphs (DRRs) and DRRs created by planning CT images. The active volume of the ionization chamber was located



**Fig. 2.** PSQA measurement setup: (a) SDVP with Exradin A16 micro-chamber and (b) a customized EBT3 film.



**Fig. 3.** Film calibration using RW3 water-equivalent phantom: (a) Absolute dose measurement setup with Farmer chamber, (b) EBT3 film placed at the same position, and (c) the calibration curve for EBT3 film. The measured pixel values were fitted by an exponential function.

in a gentle dose gradient region within target volumes.

## 2. Radiochromic EBT3 films and digitization

Gafchromic self-developing EBT3 films are widely used for the dosimetric verification of treatment planning systems and more generally for the QA of linear accelerators. EBT3 films have a high spatial resolution ( $\sim 25$   $\mu\text{m}$ ) recommended for the quality control of small fields and high-gradient dose distributions.

To correctly evaluate the gamma analysis, we made the film calibration curve representing the relationship between dose and intensity in the range of 0.1 Gy to 18 Gy. The absolute dose was measured using Farmer chamber at 5 cm depth from the phantom surface (Fig. 3a). EBT3 Films

were then irradiated within a solid water slab phantom at 5 cm depth at source-to-surface distance (SSD) of 100 cm by using a 6 MV photon (Fig. 3b). The EBT3 film was scanned and digitized 1 hr after irradiation by the Vidar scanner and analyzed using RIT software (Radiological Imaging Technology, CO, USA). The digitized pixel value was the range of  $0-2^{16}-1$ . To consider the measurement uncertainty, the calibration curve was fitted by an exponential function (Fig. 3c).

## 3. PSQA plan and acceptance criteria

We used MultiPlan 5.1.2 (Accuray Inc., CA, USA). QA template plan was created using fiducial tracking method, which is compatible with all of the tracking method for



patient plans. The sensitive area of the ionization chamber and the film area were selected as the volume of interests (VOIs) on the QA template plan. When creating PSQA plan, a target in patient plan was corresponded to the VOI representing the sensitive area of the ionization chamber. MU was then rescaled to reduce the beam delivery time. The calculated coronal view representing 2D dose distribution was exported from MultiPlan.

The gamma analysis was conducted for all CyberKnife plans. Acceptance criteria for dosimetric accuracy were  $\pm 5\%$  for the point dose measurement and  $\geq 90\%$  gamma passing rate using 3%/3 mm, applied 10% threshold dose, respectively.<sup>8)</sup> The point dose error was calculated as  $[(D_{\text{meas}} - D_{\text{cal}})/D_{\text{cal}}] \times 100\%$ .  $D_{\text{meas}}$  means measured dose by ion chamber and  $D_{\text{cal}}$  is a calculated dose by treatment planning system. Under 10 mm fixed cones, the correction factor was applied to measured dose. The point dose error was calculated as  $[(D_{\text{meas}} \times \text{CF} - D_{\text{cal}})/D_{\text{cal}}] \times 100\%$ . CF is correction factor for ion chamber considering small field effect.<sup>9-11)</sup>

## Results

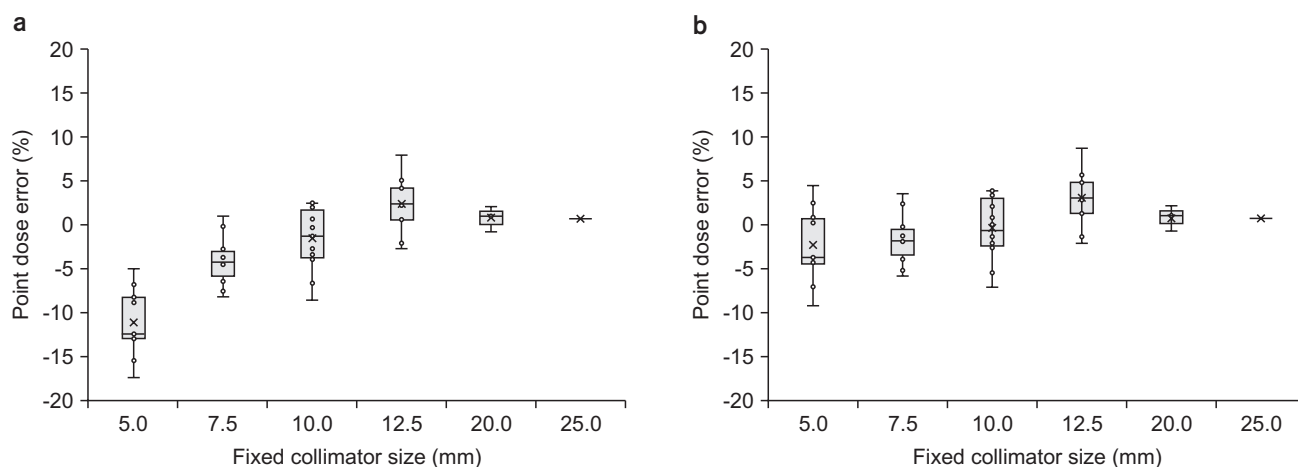
Fig. 4 shows the point dose difference between the calculated and measured doses when using the fixed collimator with cone size of 5.0 mm, 7.5 mm, 10.0 mm, 12.5 mm, 20 mm, and 25 mm. In particular, the point dose error was underestimated as  $-11.3\%$ ,  $-4.1\%$  and  $-1.5\%$  for fixed cones of 5 mm, 7.5 mm and 10.0 mm, respectively. These underesti-

mations depended on the size of the fixed collimator due to volume effect of a detector and charged particle disequilibrium. Based on the correction factor calculated by Monte Carlo simulation of A16 microchamber in CyberKnife M6,<sup>9)</sup> we corrected the measured dose by applying 1.099, 1.025, and 1.013 for fixed cones of 5.0 mm, 7.5 mm, and 10.0 mm, respectively. When these correction factors were applied to fixed cones of 5 mm, 7.5 mm, and 10.0 mm, the range of the point dose error was significantly decreased as  $-4.8\%$ ,  $-2.2\%$  and  $-0.7\%$ , respectively. Thereby, the point dose error were within  $\pm 5\%$  of tolerance and failed plans were only a few percentages outside tolerance.

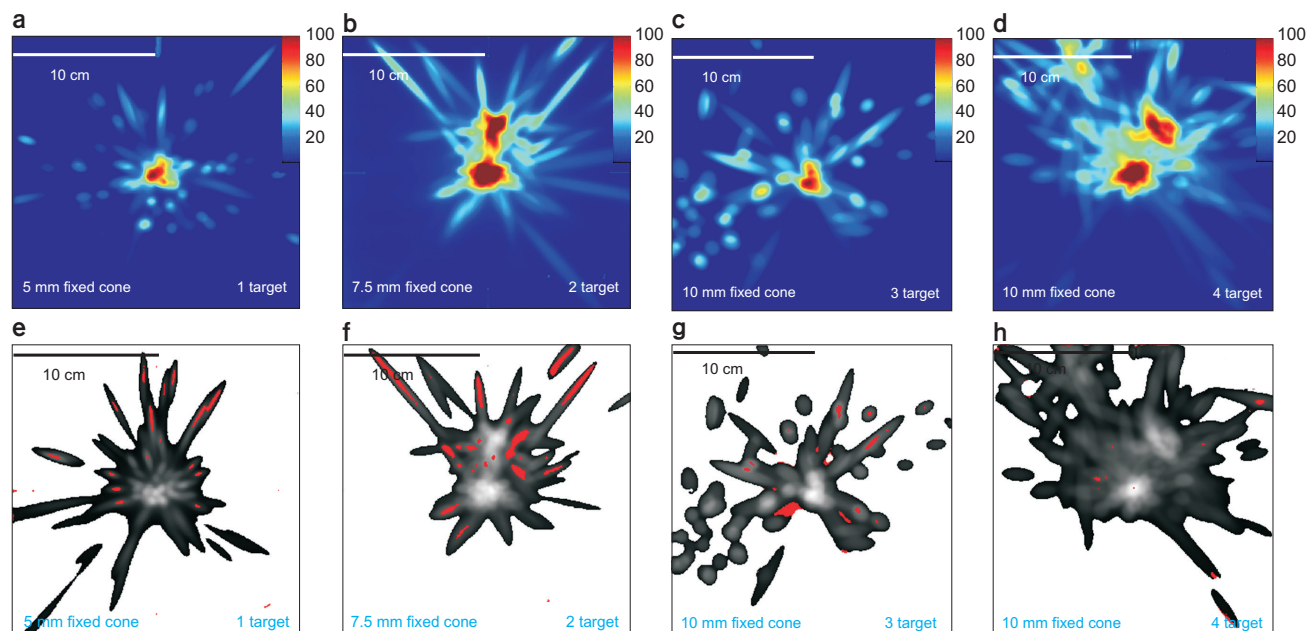
The dose distribution of multiple tumors had patterns depending on the number and position of targets (Fig. 5a). Dose distribution for multiple tumors can be confirmed in the film plane (Fig. 5b). Although the maximum dose of the target did not appear on the film, the gamma distribution in the film made it possible to verify the dose and beam direction for multiple tumors. In Fig. 6, we analyzed the gamma passing rate for the size of the fixed collimator and the number of tumors. The mean gamma passing rates for all cases was 96.1%. Based on results, gamma passing rate was not dependent on the size of fixed collimator and number of tumors.

## Discussion

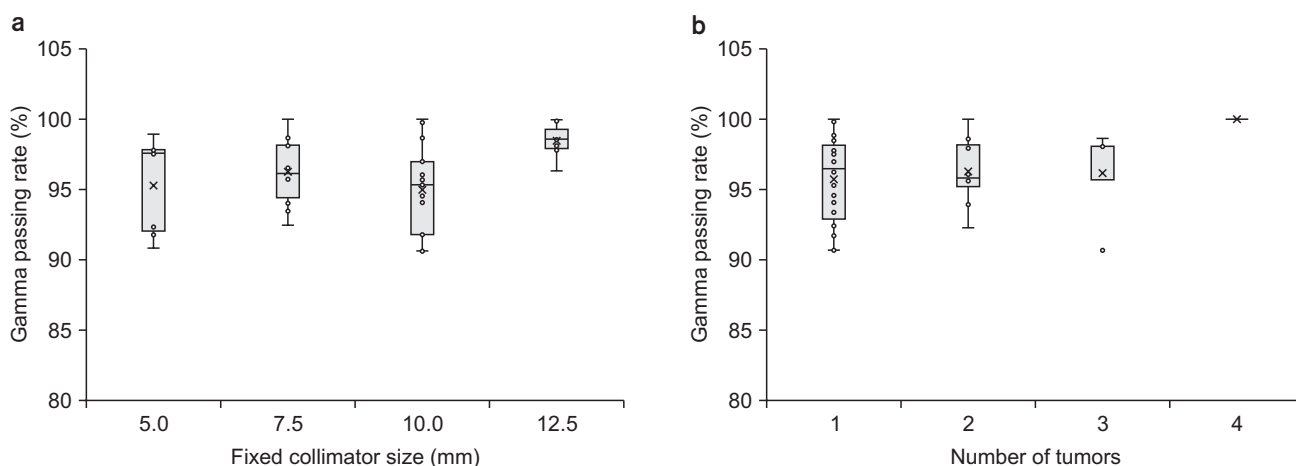
PSQA was used to confirm that the Cyberknife plan was delivered correctly. For brain tumors, fixed collimators



**Fig. 4.** Point dose error applied (a) without correction factor and (b) with correction factor by Monte Carlo simulation [10]. Boxes represent the interquartile range and horizontal lines inside each box represent the median.



**Fig. 5.** Dose (a–d) distributions for CyberKnife plans with various cone sizes and the number of targets and its gamma (e–h) pass/failure (gamma index >1 is red color). (a) and (e) results of 5 mm fixed cone and single target. (b) and (f) 7.0 mm fixed cone and 2 targets. (c) and (g) 10.0 mm and 3 targets, (d) and (h) 10.0 mm fixed cone and 4 targets.



**Fig. 6.** Gamma passing rate related to (a) the size of the fixed collimator and (b) the number of tumors. Boxes represent the interquartile range and horizontal lines inside each box represent the median.

were used to achieve high target coverage. In this study, we observed that the point dose measured through the chamber was underestimated by the collimator size. Therefore, it is necessary to apply a correction factor to the volume of ion chamber and fixed collimator in case of small size tumors. Previous studies have reported that a correction factor using a single fixed collimator can be applied to a point dose measurement, but composite collimators cannot be

applied.<sup>11)</sup> Our CyberKnife plan used only one fixed collimator. It allowed us to implement a correction factor to adjust the point dose measured with the A16 ion chamber. As a result of applying the correction factor, we confirmed that the point dose error of CyberKnife plan was within  $\pm 5\%$ . As a result of gamma evaluation using EBT3 film, we found that most plans have a gamma passing rate of over 90%. We also confirmed that the fixed collimator size or the number

of target is independent of gamma passing rate. It affirmed that PSQA using A16 microchamber and EBT3 film is sufficient to verify the accuracy of the delivery.

## Conclusion

We have demonstrated that SDVP including microchamber and EBT3 film can be considered as PSQA to ensure the dosimetric and mechanical accuracy of small and multiple targets in CyberKnife with fixed collimators. In particular, the correction factors for A16 microchamber should be applied to the small fixed collimators less than 10 mm.

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## Conflicts of Interest

The authors have nothing to disclose.

## Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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